Final project report: VR Guided Surgery – SDF Based Guidance and Safety

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Abstract

Lack of non-technical skills such situational awareness (SA) has been associated with human error and reduced patient safety in the operating theater. Despite their importance, surgical simulators and training curriculum's focus on developing strong technical skills and often neglect the development non-technical skills. In this work, we leverage a simulation environment based on AMBF+ for skull-base surgery to develop and test feedback modalities aimed to improved the awareness of critical anatomical structures. To provided feedback in real-time, signed distance fields (SDF) for each anatomy are computed at the beginning of the simulation that allow to easily query the distance between the simulated drill tip and nearby anatomies. Using this distance information different visual and feedback modalities were develop to improve procedure safety and training experience.

1 Team members, mentors

Team members: Juan Antonio Barragan and Hisashi Ishida
Mentors: Max Li, Adnan Munawar, Prof. Misha Kazhdan, Prof. Russell Taylor

2 Project relevance and significance

2.1 Medical Background

Mastoidectomy is a common procedure to treat an infection in mastoid air cells. The surgeon will cut the ear remove the hollow bone by drilling the temporal bone. This procedure can be highly challenging because it requires high precision to preserving the critical structures such as semicircular canals, sigmoid sinus, and facial nerves. Damaging those important structures can result in subsequent fatal complications, which vary from temporal or permanent loss of ringing in the ear or dizziness, partial or total loss of hearing, facial nerve palsy, or even death of the patients.

Figure 1: (Left) Mastoidectomy[1], (Right) Important structures concerned in the mastoidectomy[2]

2.2 Technical background

Previous work from Hopkins has developed a virtual simulator, AMBF(Fig.2), for volumetric drilling. This simulation leverages on segmented CT images to create an anatomically accurate drilling simulator environment which the users observe via a stereoscopic display. This simulator is particularly powerful because it allows users to practice surgical procedures while also generating data for surgical computer vision algorithms.

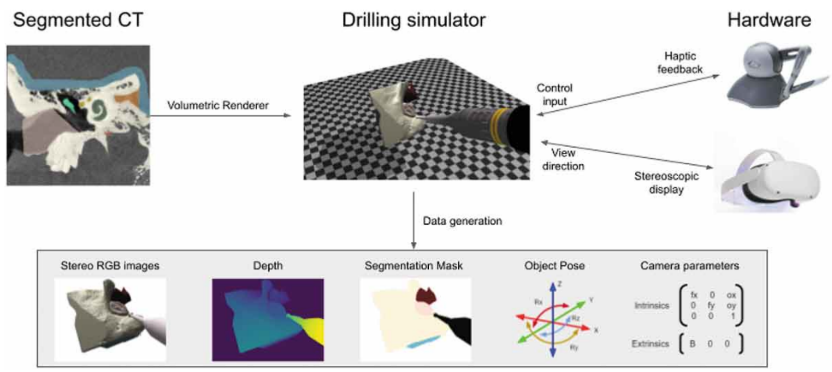

Figure 2: System Overview of AMBF[4]

Currently, the simulation environment does not provide safety cues related to the distance between the drill and critical anatomies. Although a warning message is provided when the user collides with an anatomy, this is not enough feedback to teach the train how to avoid such a dangerous situations in a real procedure. Secondly, the simulator lacks the capability of providing haptic feedback to secure the patient safety. We believe that improving these two aspects will result in improved safety for the patient and reduce workload of the surgeons.

2.3 Aim and Significance

Specific Aim 1: Implement an algorithm to calculated signed distance fields SDF of anatomical structures represented in voxel grids.

Calculated SDF will be used to monitor the distance between the tool tip and the static anatomy in real-time. By knowing the distance to the different anatomical structures in real-time will allow to provide feedback to improve situational awareness of the user.

Specific Aim 2: Propose SDF based feedback with different modalities.

Provide additional safety for a VR guided surgery and reduce workload in the surgery.

Specific Aim 3: Expand our method to adapt SDF method for the time-varying volume.

Provide useful guidance for drilling the temporal bone.

Specific Aim 4: Write a conference paper .

Share quantitative assessment results of our proposed SDF based feedback with the medical and engineering community

3 Technical summary

To improve the situational awareness and safety, it is necessary to calculate the distance between the drill tip and the anatomies in real-time. This information can be then utilize to prevent the user from drilling a critical anatomy or just to improve the user's awareness of close critical anatomical structures as he performs the procedure. This distance could be naively calculated by iterating over the voxel representation of the environment after each drill update. This however is a computationally inefficient algorithm that can result in high delays in the system.

As an alternative, signed distance fields (SDF) can be calculated for each of the anatomies in the simulation. A SDF function will generate a new voxel map in which the voxel's value is the minimum distance between that specific voxel location and the the reference anatomy. After obtaining a SDF for each of the different anatomies in the simulation, the calculation of the minimum distance between the drill tool tip and a specific anatomy can be speed up significantly. Obtaining this distance would only require to query the SDF in the voxel where the drill is currently located. In this regard, SDF functions need to be calculated for all static anatomies at the beginning of the simulation to provided feedback to the user.

To achieved the goals of project, the work will be divided into three different phases each one with an unique and specific objective. Phase 1 will be focusing on integrating SDF functions into the drilling simulation for objects that do not change their volume. Phase 2 will be focusing on using the calculated SDF to improve the situational awareness of the user via haptic or visual feedback. The last phase of the project will be concerned with optimizing the calculation of SDF to perform them in real-time.

3.1 Aim 1: Integration of SDF calculation algorithms to AMBF+

A SDF c++ library was adapted to work with the voxel grid that contains the anatomy in the volumetric simulation. The selected library used the method proposed by Saito and Toriwaki, 1994[6] to calculated the SDF and it was chosen because it allows for parallelization. To calculate the SDF a list of images containing the voxel grid was fed to the algorithm. As an output the algorithm produces a new a voxel grid containing the distance between a specific voxel and the anatomy. To load the precomputed SDF grids, the simulation plugging was modified with a reading function that uploads the SDF at initialization. Additional information such as the name of each anatomy and the assigned color in the simulation are also uploaded. SDF grids are only calculated once based on the assumptions that critical anatomies will not change their volume.

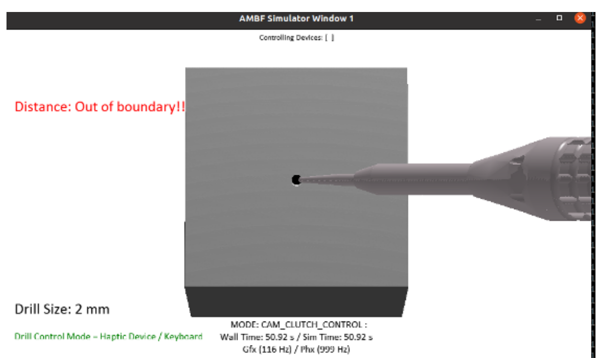

Figure 3: Cube anatomy used to test the correctness of the SDFs

To test the correctness of the SDF grid, a cube toy anatomy aligned to the voxel axis was used (see figure 3. With this simple anatomy all voxels lying on a plane parallel to the cube anatomy will have the same value. At run time, both the SDF and anatomy are loaded at initialization. At runtime the SDF grids are used to provided feedback to the user as he performs the drilling exercise. The complete system architecture can be observed in figure 4.

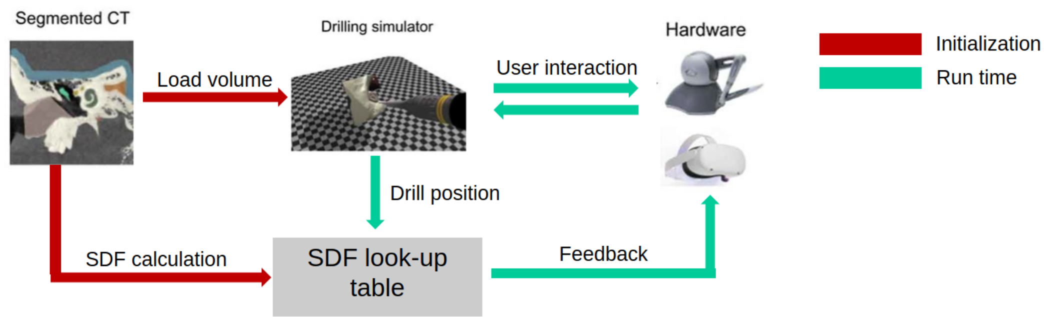

Figure 4: Phase 1 system architecture

3.2 Aim 2: Development of SDF based feedback modalities

This phase aims to implement helpful feedback with different modalities for surgeons using the SDF look-table calculated in Phase 1. We have developed three different modalities: 1)Visual feedback, 2) Haptic feedback, 3) Auditory feedback to improve situational awareness.
From Aim 1, we convert the frame so that the we can get the direction from the tooltip to the closest anatomy in the world coordinate. Please refer to the following diagram for the frame transformation.

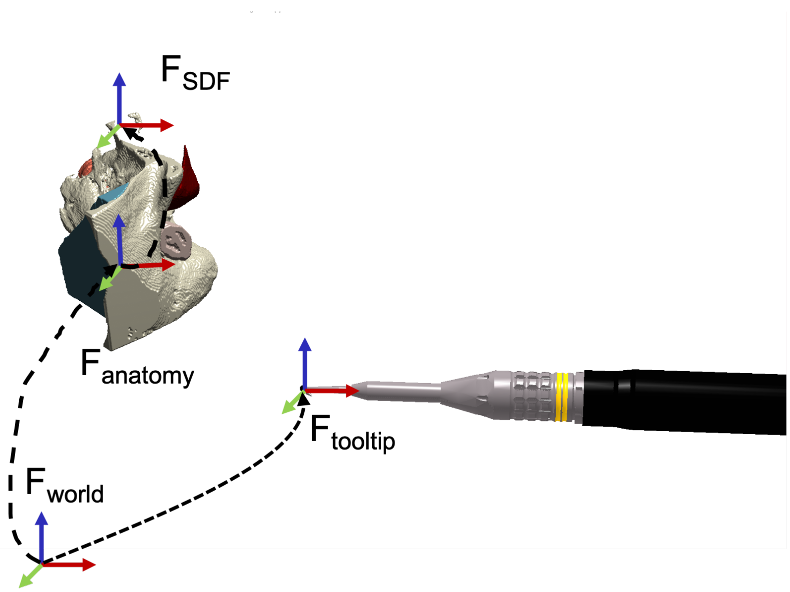

Figure 5: Frame transformation diagram

3.2.1 Visual feedback

In the previous simulation, a warning message was being overlapped on the screen to notify a surgeon about their mistake. This warning was shown when the drill hit the critical anatomies. This message was very intuitive, but also very disturbing since it blocked the surgeons' vision.

Consequently, we focused on securing the surgeon's freedom and visually providing helpful information during the operation. We have successfully implemented the method to display the name of the closest anatomy, distance to the closest critical anatomy, and direction of the force to avoid the anatomy. All the texts correspond to the color in the simulator so that it is intuitive to perceive. Furthermore, all the visual information was displayed in a pair of stereoscopic images to provide a sense of depth in the simulation. We already tried out this system with Head Mount display.

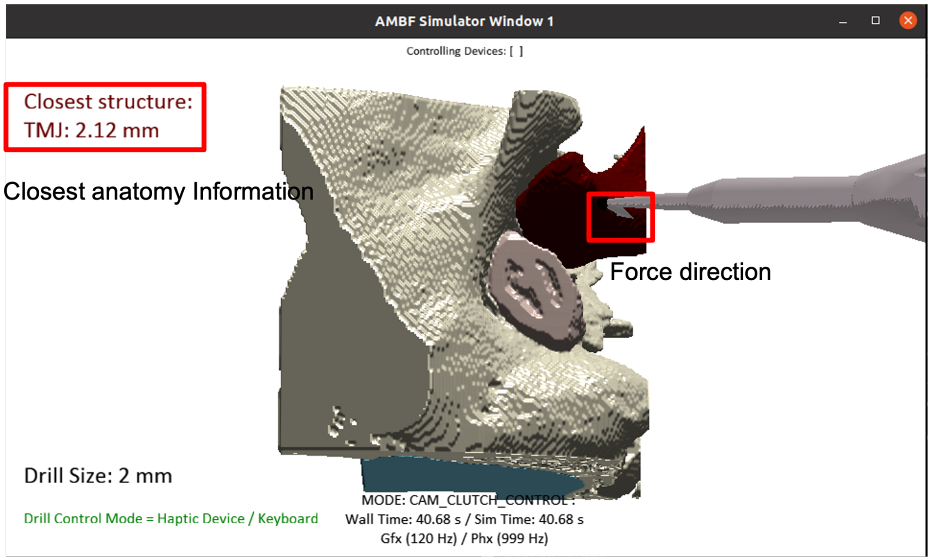

Figure 6: Proposed visual feedback.

After consulting with Dr. Creighton, we decided to get rid of the arrow for the direction of the force.

3.2.2 Haptic feedback

AMBF+ adopts CHAI3D's [3] finger proxy collision algorithm [5] to provide haptic feedback by simulating the collision with the surface of the volume. The movement of the tool will be simulated using the proxy/goal spheres such that the proxy sphere cannot cross the boundary of the surface or volume while the goal sphere will move freely to match with the tool. Force feedback will be generated proportional to the distance between the proxy and the goal spheres. We add an additional force term, $F_{SDF} \in R^3$, on top of original force from the drilling.Formulation of this SDF based force can be written as follows:

$$F_{SDF} = -F_{max}(1 - \frac{|\vec{d}|}{d_{force}})\frac{\vec{d}}{|\vec{d}|}(if \quad d < d_{force}) \tag{1}$$

And the this force has a upper limit of F_max.We have tuned the parameter, $F_{max} = 0.5N$ and threshold for activating this force d_{force} according to the pilot study with Dr. Creighton and the values are shown in the Table 1.

3.2.3 Auditory feedback

We implemented the auditory feedback to notify the surgeons' when the tool tip was about to collide with a critical anatomy. Surgeons are familiar with this kind of auditory feedback, and it will serve as a situational awareness method that is less disturbing during the surgery. In detail, we provide a beeping sound when the drill is closer than d_{audio} to the critical structures(Table.1).Furthermore, after consulting with surgeons, we found that audio feedback can be a initial situational awareness for approaching the critical anatomy so that the threshold for this audio can be larger than that of force.

Structure	Force threshold [mm]	Audio threshold [mm]
IAC	1.0	1.0
Dura	0.5	1.0
TMJ	1.0	1.0
ICA	1.0	1.0
Malleus	1.0	1.0
Incus	0.5	1.0
Stapes	0.5	1.0
Bony Labyrinth	0.5	1.0
Superior Vestibular Nerve	1.0	1.0
Inferior Vestibular Nerve	1.0	1.0
Cochlear Nerve	1.0	1.0
Facial Nerve	0.25	0.5
Chorda Tympani	0.25	0.5
Vestibular Aqueduct	1.0	1.0
EAC	0.5	1.0

Table 1: Force and audio feedback thresholds for every structures in the simulator.

3.3 Aim 3: Online SDF method for time-varying volume

We were originally planned to expand our method to adapt SDF method for the time-varying volume but we decided to focus more on the evaluation of our situational awareness method proposed in Phase1 and 2.

4 User Study

We are planning to conduct a preliminary experiment on May 12-14. The details are as follows:

1. Subjects: 3 (Expert, Intermediate, no-surgeon)
2. Anatomy: 4
3. Experimental conditions:
   (a) C1: without no assistance method,
   (b) C2: with all the feedback modality
4. Evaluation Metrics
   - Completion Time
   - Number of critical anatomies' voxels removed during the procedure
5. Questionnaire NASA TLX, Preference of feedback modality

The goal of the user study is evaluating if the SDF feedback modalities help the surgeon improve their task performance.

5 Technical Appendices

1. Github:
   https://github.com/jabarragann/volumetric_drilling
   Onedrive:
   https://livejohnshopkins-my.sharepoint.com/:f:/g/personal/hishida3_jh_edu/EsBUx0xL_yNHuutXac2dK_sBW6H3FxhiemT0R9KAEkNKXg?e=hefgC6

References

[1] Mastoid surgery animation. https://www.youtube.com/watch?v=ZRxG_AmDaLI. Accessed: 2022-02-22.

[2] Tympanoplasty with cortical mastoidectomy? http://entsurgeonkemptonpark.co.za/tympanoplasty-cortical-mastoidectomy-2/. Accessed: 2022-02-22.

[3] Francois Conti, Federico Barbagli, Dan Morris, and Christopher Sewell. Chai 3d: An open-source library for the rapid development of haptic scenes. *IEEE World Haptics*, 38(1):21–29, 2005.

[4] Adnan Munawar, Zhaoshuo Li, Punit Kunjam, Nimesh Nagururu, Andy S. Ding, Peter Kazanzides, Thomas Looi, Francis X. Creighton, Russell H. Taylor, and Mathias Unberath. Virtual reality for synergistic surgical training and data generation. 0(0):1–9. Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/21681163.2021.1999331.

[5] Diego Ruspini and Oussama Khatib. Haptic display for human interaction with virtual dynamic environments. *Journal of Robotic Systems*, 18(12):769–783, 2001.

[6] Toyofumi Saito and Jun-Ichiro Toriwaki. New algorithms for euclidean distance transformation of an n-dimensional digitized picture with applications. 27(11):1551–1565.

6 Management plan

6.1 Author contribution statement

Both Juan Antonio and Hisashi participated equally in the development of the systems and writing of the report. Juan Antonio took care of compiling the SDF libraries, organizing the code into a github repository, coding the functions to load SDF voxel grids to the simulation and coding python scripts to automize the creation and loading of SDF. Hisashi worked on the development of visual and haptic modalities using the loaded SDF, organized and created the meeting slides, and develop the code to present visual feedback on the headmount display.

6.2 Discussion of planned goals and accomplished goals

The initial plan for the project included 4 specific goals to be accomplished during the semester: (1) Implementation of SDF calculation algorithms , (2) Development of SDF based feedback modalities, (3) Evaluation of feedback modalities and writing of conference paper, and (4) implementation of real-time SDF algorithms. Out of the 4 proposed goals aim 1 and 2 were fully completed, aim 3 was partially completed at the time of this writing and aim 4 was left as future work. The main reason why the original plan was modified was because more feedback modalities were developed at the end of the semester. The reason to dedicated more time to developing better feedback modalities was that the original planned modalities would not be good enough for a user study.

1. **Minimum Deliverable(Completed)**:
   Create AMBF plugin to calculate SDFs for static objects in the volumetric drilling simulation.

2. **Expected Deliverable(Completed):**
   Using the calculated SDFs to improve the user situational awareness via haptic feedback and/or visual cues. We add audio feedback for further assistance.

3. **Maximum 1(Ongoing exected to done by May 17th):**
   Conduct the user study. We are now preparing for the experiment. We will have the result by the final presentation.

4. **Maximum 2(Future plan):**
   Optimizing algorithms to calculate SDFs of objects changing overtime in real-time, e.g., the drilling volume. We will tackle this problem in the summer.

6.3 Future work

After completing the user studies and writing the conference paper , future work should focus on the development of real-time SDF algorithms. The current implementation of the SDF algorithm takes on average 0.5 second calculate to calculate the distance field of each the anatomy, which is not enough for real-time. The key observation to improve the performance of the SDF algorithm is that anatomies to do not change significantly from frame to frame. In this regard, the original calculated SDF can be adapted to account for the small changes that occur from frame to frame.

6.4 Skills Learned

On the programming side this project help us improve our C++ knowledge as we were required to integrate several libraries into one project. Another big lesson from this project was on learning how to use the AMBF simulator. Most of this knowledge came from learning adapting the configuration files of the simulation to develop the feedback modalities. Struggling for IRB protocol and scheduling a meeting with surgeons were challenging but they have provided us useful and constructive feedback every time. Lastly, the project has allowed us to learned about designing better feedback modalities to improve the usability of the system.